

"SMALL BAND GAP SUPERLATTICES AS INTRINSIC LONG WAVELENGTH
INFRARED DETECTOR MATERIALS"

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Intrinsic long wavelength ($\lambda \geq 10 \mu\text{m}$) infrared (IR) detectors are currently made from the alloy (Hg, Cd) Te. There is one parameter, the alloy composition, which can be varied to control the properties of this material. The parameter is chosen to set the band gap (cut-off wavelength). The (Hg, Cd) Te alloy has the zincblend crystal structure. Consequently, the electron and light-hole effective masses are essentially inversely proportional to the band gap whereas the heavy-hole effective mass is essentially independent of the band gap. As a result, the electron and light-hole effective masses are very small ($M_c^*/M_0 \sim M_{lh}^*/M_0 \leq 0.01$) whereas the heavy-hole effective mass is ordinary size ($M_{hh}^*/M_0 \sim 0.4$) for the alloy compositions required for intrinsic long wavelength IR detection. This combination of effective masses leads to rather easy tunneling and relatively large Auger transition rates. These are undesirable characteristics, which must be designed around, of an IR detector material. They follow directly from the fact that (Hg, Cd) Te has the zincblend crystal structure and a small band gap.

In small band gap superlattices, such as HgTe/CdTe, In(As, Sb)/InSb and InAs/(Ga, In)Sb, the band gap is determined by the superlattice layer thicknesses as well as by the alloy composition (for superlattices containing an alloy). The effective masses are not directly related to the band gap and can be separately varied. In addition, both strain and quantum confinement can be used to split the light-hole band away from the valence band maximum. These "band structure engineering" options can be used to reduce tunneling probabilities and Auger transition rates compared with a small band gap zincblend structure material. We discuss the different "band structure engineering" options for the various classes of small band gap superlattices.

SMALL BAND-GAP SUPERLATTICES AS INTRINSIC IR DETECTOR MATERIALS

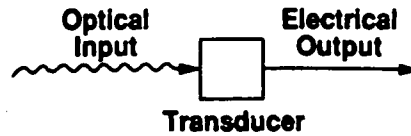
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C. Mailhot - Lawrence Livermore

OUTLINE

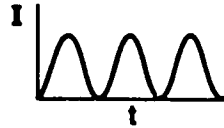
- 1) Introduction**
- 2) Band structure engineering**
 - a) Zincblende structure materials**
 - b) Small band-gap superlattices**
- 3) An example InAs/GaInSb**
- 4) Conclusion**

IR DETECTORS



Optical Input

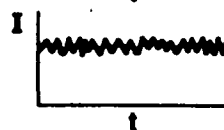
1) Signal



2) Background



3) Shot noise on background



$$V_N = \left[V_1^2 + V_2^2 + \dots \right]^{1/2}$$

**BEST TRANSDUCER DOESN'T
DEGRADE S/N (BACKGROUND LIMITED)**

$$V_N^2 = \text{STUFF} \left[\underbrace{\frac{\eta Q_B \tau}{d}}_{\text{SHOT NOISE ON OPTICAL BACKGROUND}} + \underbrace{n_T}_{\text{IDEAL DEVICE BEHAVIOR}} + \dots \right]$$

SHOT NOISE ON OPTICAL BACKGROUND

IDEAL
DEVICE
BEHAVIOR

- 1) MINORITY CARRIER DENSITY; INTRINSIC
- 2) THERMALLY IONIZED CARRIER DENSITY; EXTRINSIC

NONIDEAL
BEHAVIOR

DIODE TUNNELING;
1/f ETC.

$$\text{Want } \frac{\eta Q_B \tau}{d} > n_T$$

$$\text{Min } \frac{n_T}{\alpha \tau}$$

$$d \sim \alpha^{-1}$$

$$\sim e^{-E_t / kT}$$

BAND STRUCTURE PARAMETERS



PARAMETERS

PHYSICAL PROCESS

E_g

ABSORPTION THRESHOLD

$M_e^* (M_{\perp}; M_{||})$

RECOMBINATION TIMES
(AUGER; RADIATIVE)

$M_h^* (M_{\perp}; M_{||})$

ABSORPTION COEFFICIENT

P_{eh}

TRANSPORT (TUNNELING;
DIFFUSION)

DESIGN PROCESS

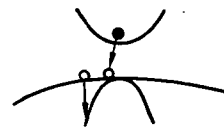
- 1) MATERIAL DESIGN
- 2) DEVICE DESIGN

AVOIDABLE PROCESSES

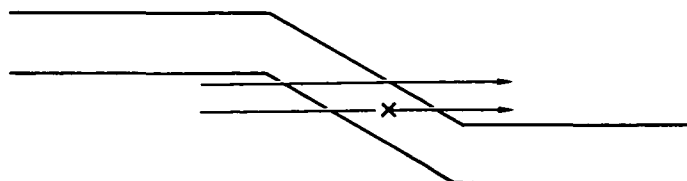
AUGER



$$e^{-\frac{E_g}{kT} \frac{M_e}{M_h}}$$



TUNNELING



K•P THEORY

$$\left[\frac{p^2}{2M} + V \right] \psi = \epsilon \psi$$

$$\psi = e^{i\mathbf{k} \cdot \mathbf{r}} U^{\mathbf{k}}$$

$$\left[\frac{p^2}{2M} + \frac{\hbar \mathbf{k} \cdot \mathbf{P}}{M} + \frac{(\hbar \mathbf{k})^2}{2M} + V \right] U^{\mathbf{k}} = \epsilon U^{\mathbf{k}}$$

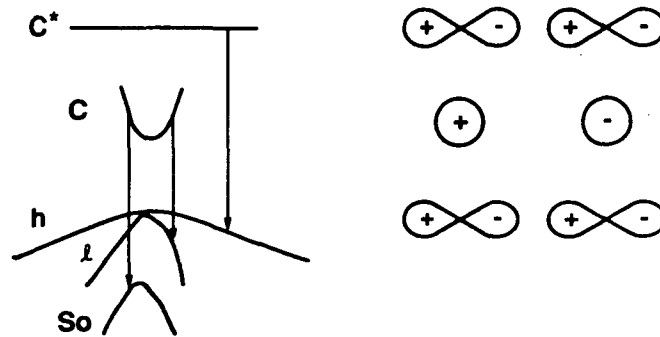
AT ZONE CENTER ($\mathbf{k} = 0$)

$$\left[\frac{p^2}{2M} + V \right] U_j^0 = \epsilon_j^0 U_j^0$$

$$U = \sum_j a_j U_j^0$$

$$0 = \sum_j \left[\left(\epsilon_j^0 + \frac{(\hbar \mathbf{k})^2}{2M} - \epsilon \right) \delta_{ij} + \frac{\hbar \vec{k} \cdot \vec{P}}{M} \langle U_i | \vec{P} | U_j \rangle \right] a_j$$

ZINCBLLENDE STRUCTURE MATERIALS

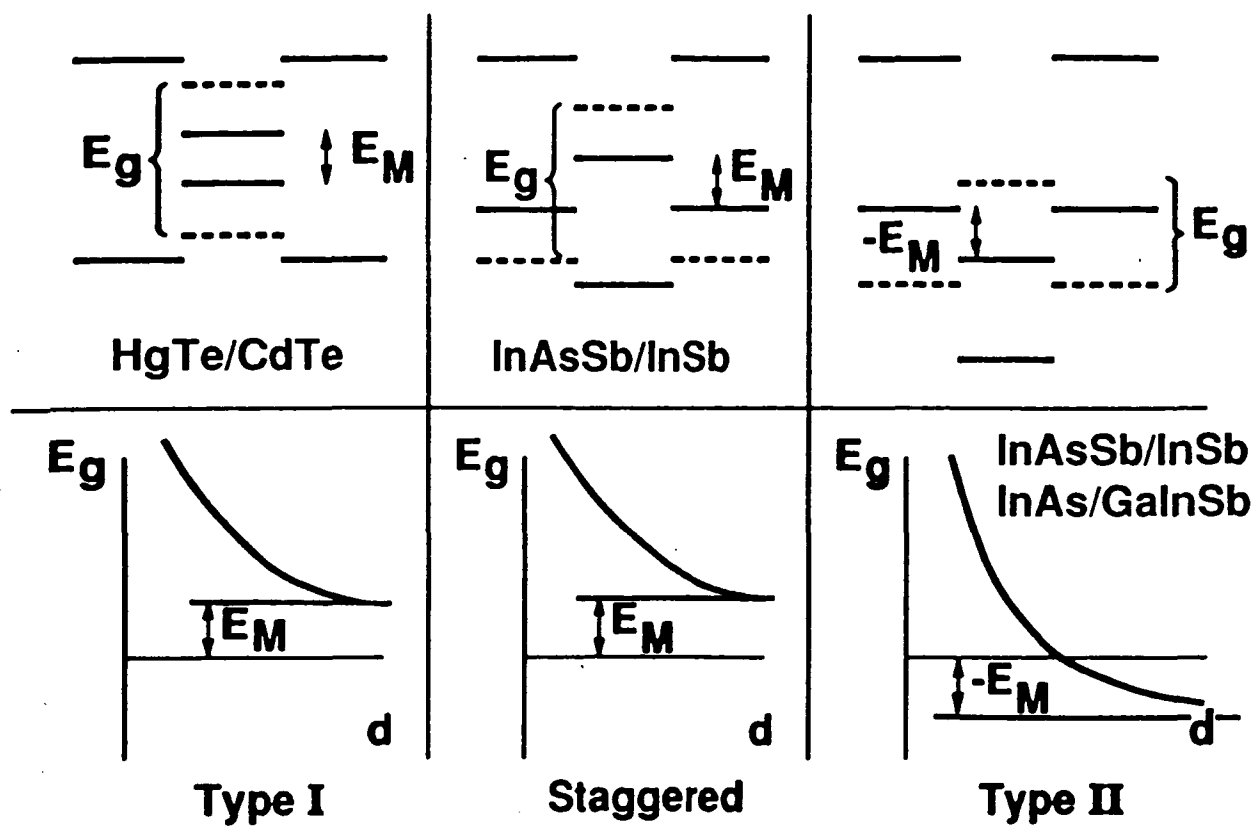


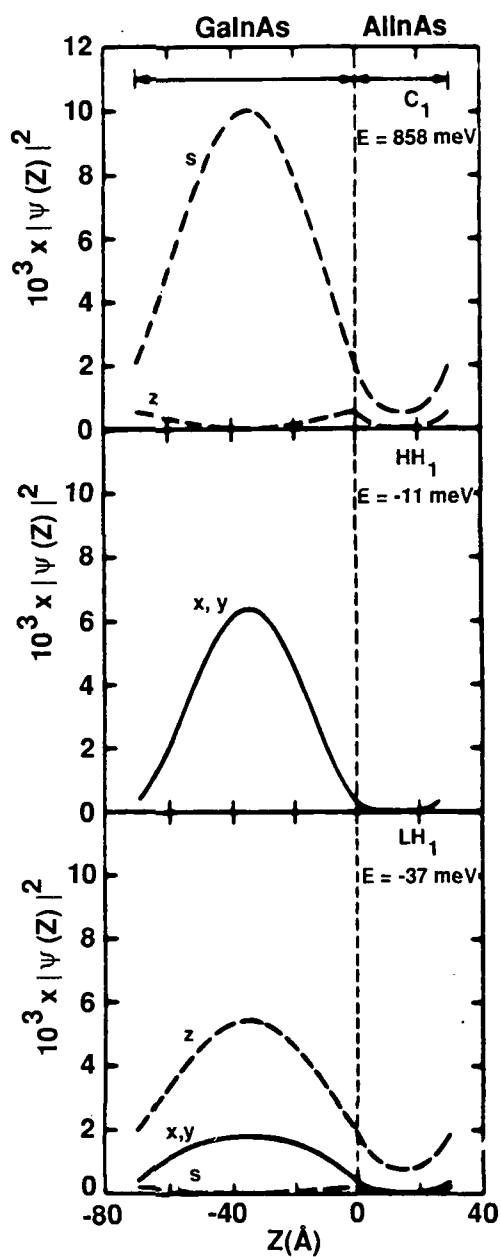
ELECTRON AND LIGHT HOLE (SMALL E_g)
(LARGE Δ)

$$\begin{vmatrix} \epsilon_c - \epsilon & \alpha \\ \alpha^* & \epsilon_v - \epsilon \end{vmatrix} = 0 \quad \alpha = \sqrt{\frac{2}{3}} i P k$$

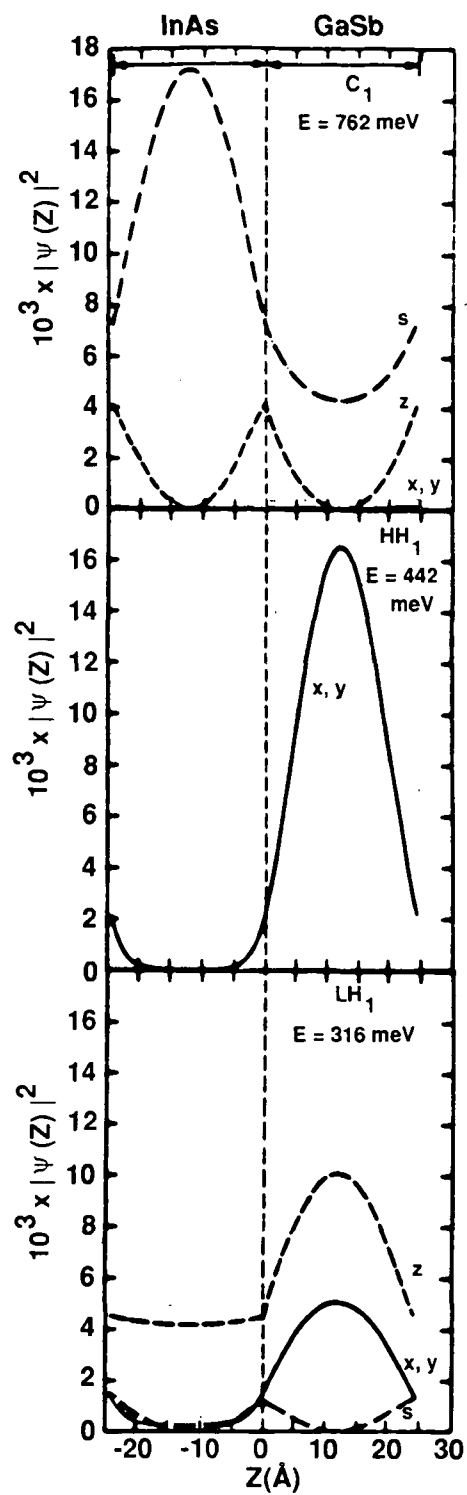
$$\frac{M_0}{M^*} = \pm \frac{2M}{\hbar^2} |P|^2 \left(\frac{2}{3} \left(\frac{1}{E_g} \right) \right)$$

SMALL BANDGAP SUPERLATTICES



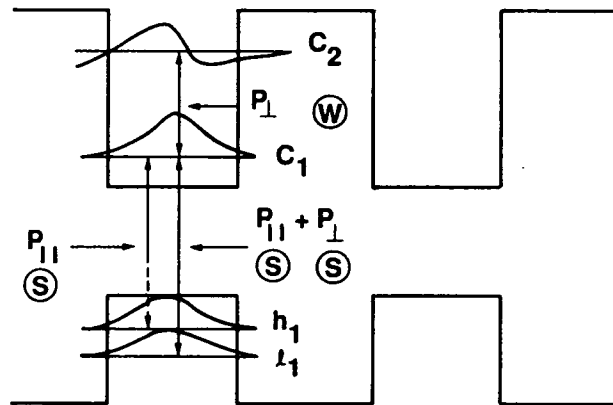


TYPE I



TYPE II

K·P THEORY SUPERLATTICE SIMPLE CASE



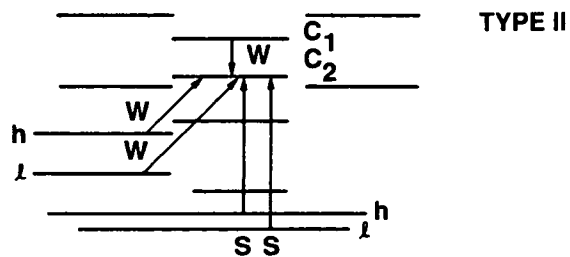
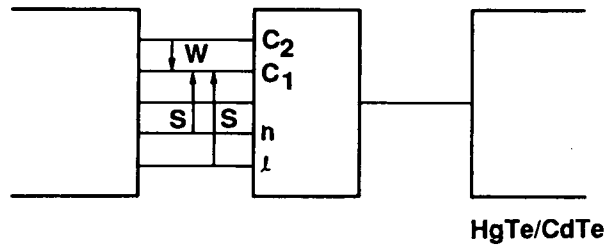
$$\psi = F U$$

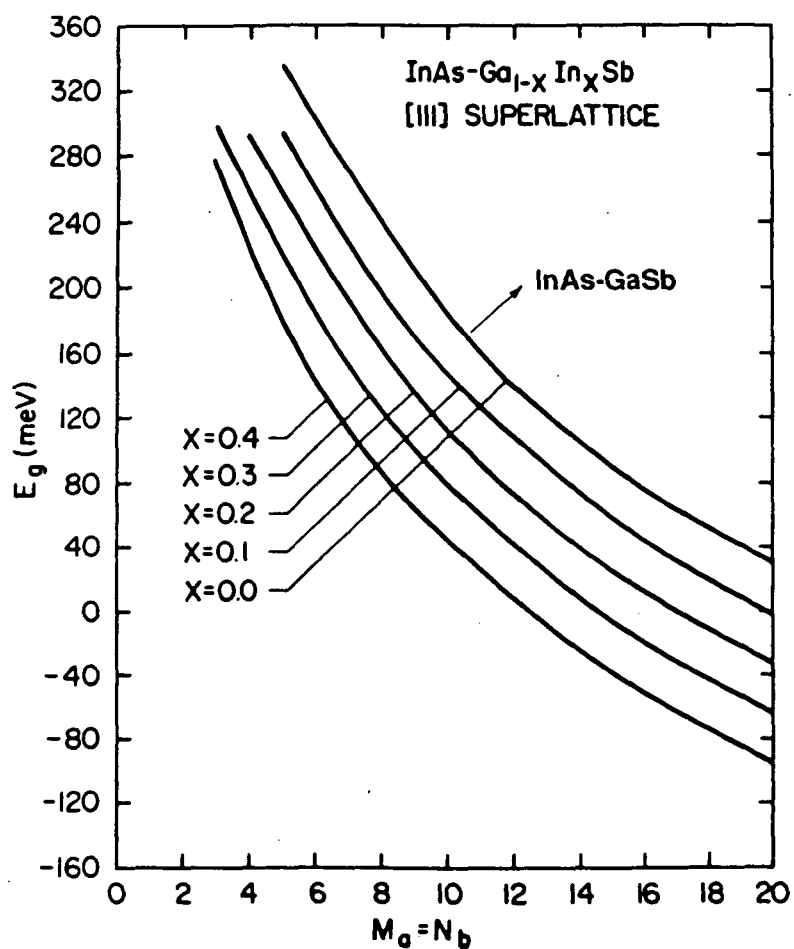
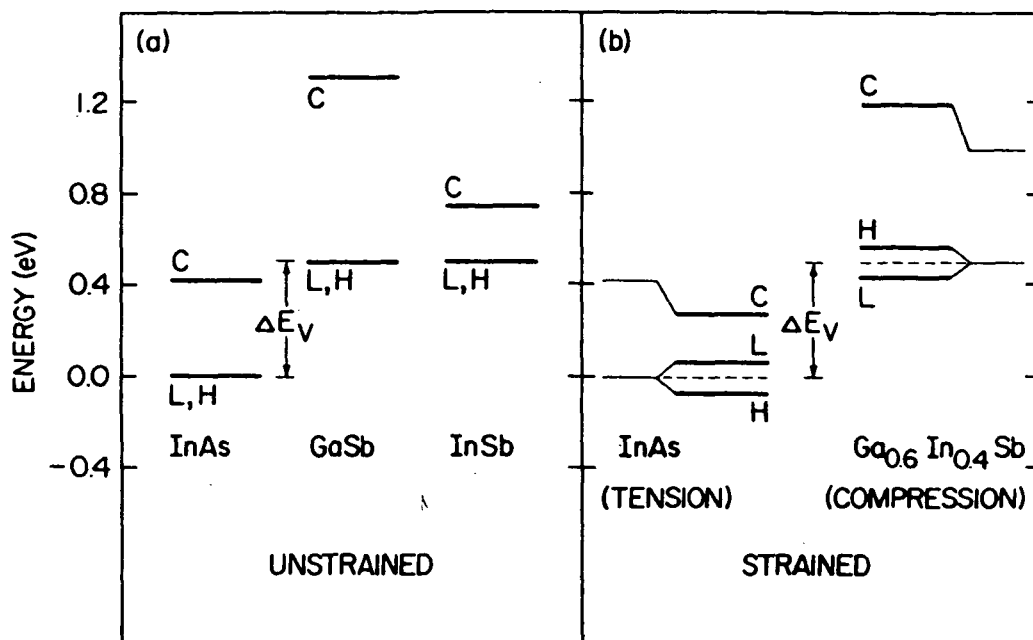
$$\langle F_1 U_1 | P | F_2 U_2 \rangle$$

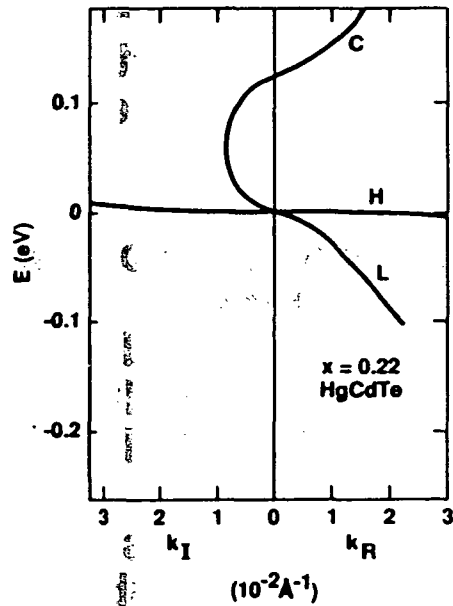
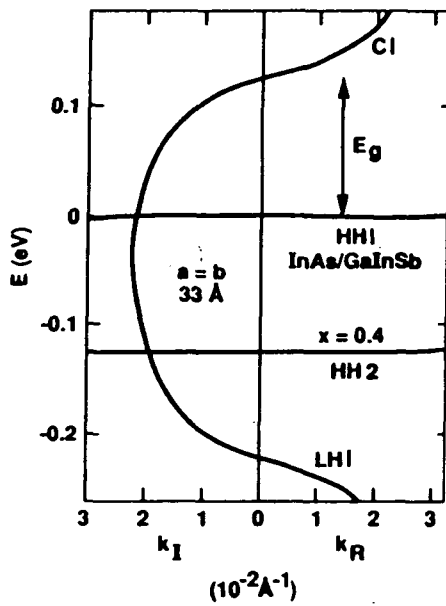
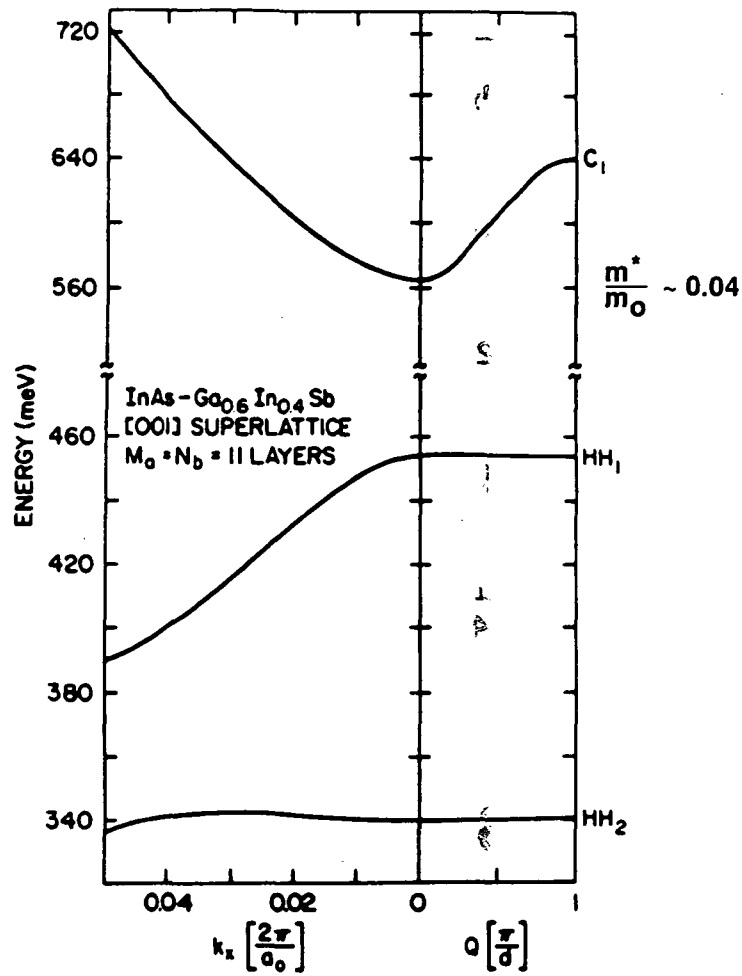
$$\sim \langle F_1 | F_2 \rangle \langle U_1 | P | U_2 \rangle \quad S$$

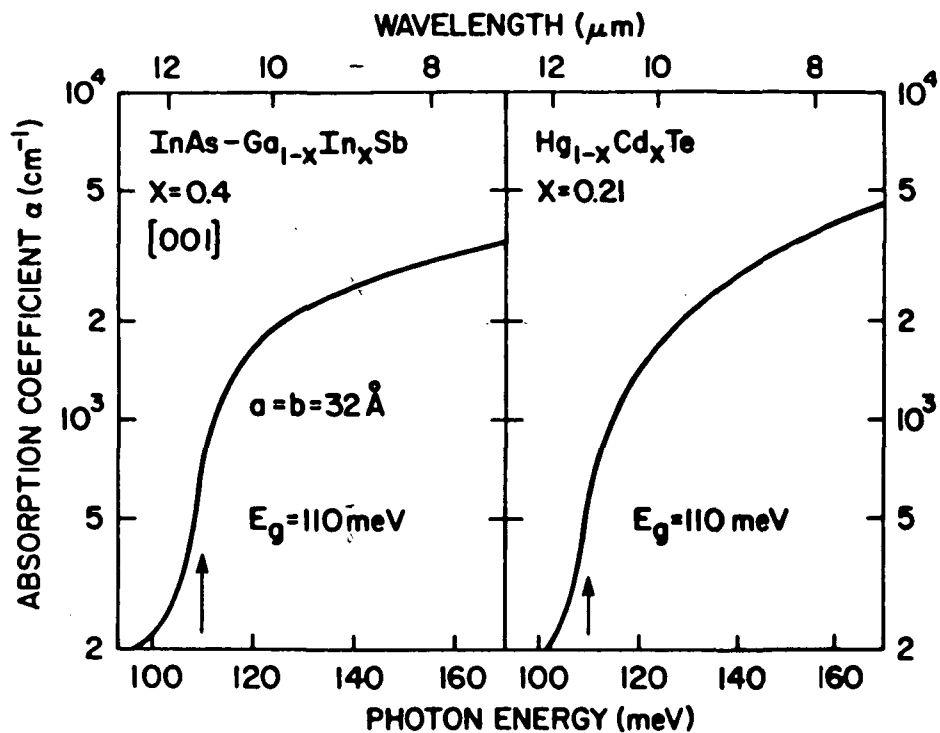
$$+ \langle F_1 | P | F_2 \rangle \langle U_1 | U_2 \rangle \quad W$$

K·P THEORY SUPERLATTICE SMALL GAP









SUMMARY

- 1) Small band-gap superlattices offer band structure engineering options which make them interesting IR materials
- 2) Examples of such superlattices include:
 - a) HgTe/CdTe
 - b) InAsSb/InSb
 - c) InAs/GaInSb
- 3) Predictions on E_g and α in InAs/GaInSb